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SHALE GAS PLAYS OF THE SOUTHERN APPALACHIAN THRUST BELT

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ABSTRACT

Multiple shale gas plays are active in Cambrian and Devonian strata of the southern Appalachian thrust belt of Alabama, and this activity has necessitated the development of conceptual geologic models based on thrust belt geometry and kinematics to help guide shale gas exploration and development. Geologic structure is a key control on the distribution and characteristics of proven and prospective reservoirs in the southern Appalachians. Shale in the Cambrian-age Conasauga Formation is prospective in giant antiformal stacks that rest on the basal detachment of the thrust belt. Conasauga reservoirs have characteristics of fractured and microporous gas reservoirs, and high reservoir pressure in some fracture networks appears to be related to relict hydrocarbon pressure associated with thermogenic gas charge.

Shale reservoirs in the Devonian-age Chattanooga Shale and an unnamed Pre-Chattanooga shale section are prospective on fold limbs and in flat-bottomed synclines. Folds are associated with thrust faults that have a ramp-flat to listric geometry, and fault geometry determines the location and geometry of fold limbs and hinges. Fracturing in fold limbs and hinges may be associated with corridors of enhanced permeability. Fresh-water recharge along anticlinal crests may facilitate augmentation of thermogenic gas with late-stage biogenic gas. Recharge, moreover, appears to be associated with a significant volume of formation water that is co-produced with gas from the Chattanooga Shale.

INTRODUCTION

Shale is a rapidly emerging natural gas reservoir in the United States, and development has begun in a broad range of sedimentary basins. To date, most production comes from nearly flat-lying strata in the interiors of large sedimentary basins, such as the Appalachian, Michigan, and Fort Worth basins (e.g., Ettensohn, 1985; Martini et al., 1998; Hill and Jarvie, 2007). As the shale gas industry has expanded in recent years, significant exploration targets have been identified in Cambrian through Devonian strata of the southern Appalachian thrust belt of Alabama (Pashin, 2008) (fig. 1). Here, prospective shale formations can be complexly folded, faulted, and fractured, which poses numerous challenges for exploration and development.

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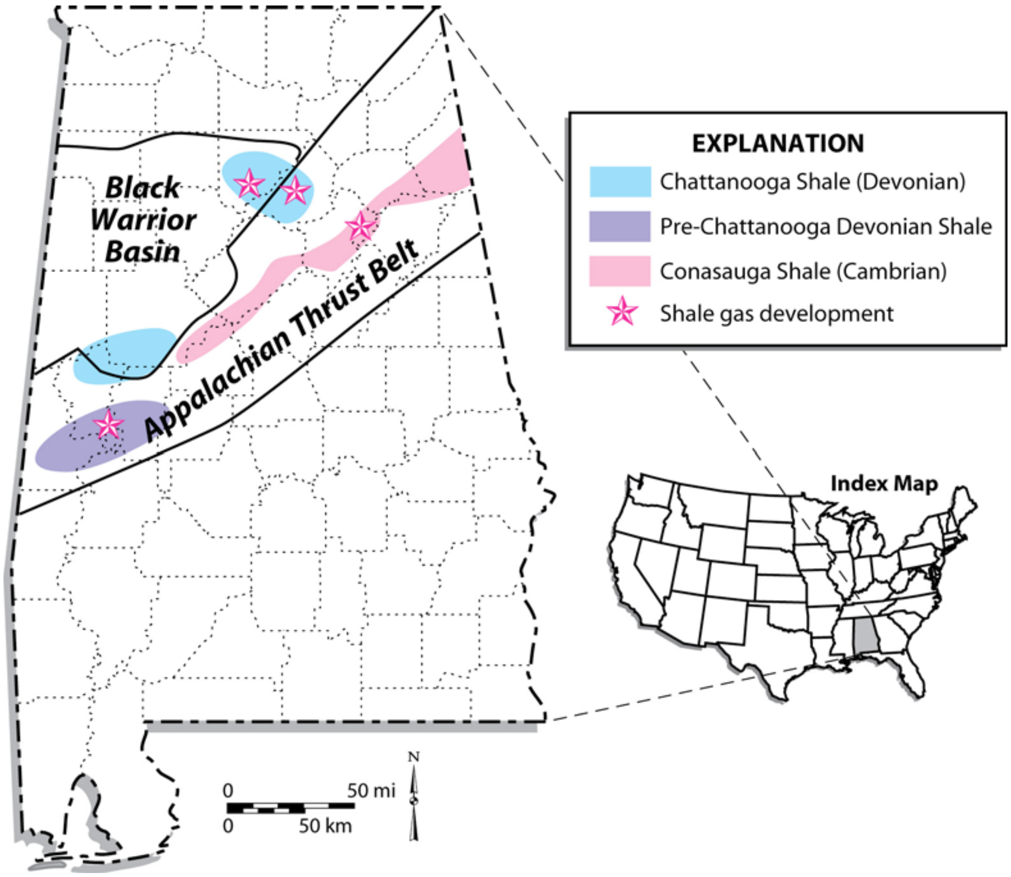

Figure 1.—Generalized map showing shale gas plays and development areas in the southern Appalachian thrust belt of Alabama.

This paper reviews the stratigraphy and geologic structure of the diverse shale gas reservoirs that are being explored in the southern Appalachian thrust belt of Alabama. Production efforts are in the early stages in this area, so the objective is to identify the geologic factors that may influence the occurrence and producibility of shale gas, thereby providing a conceptual framework that can help guide ongoing exploration and development efforts. The principal tools available to facilitate this effort are geologic maps, seismic lines, balanced structural cross sections, well logs, cores, outcrops, and production data. This paper synthesizes new research results with the large body of geological research that already exists in the southern Appalachians. This work is part of a three-year study of shale gas reservoirs in Alabama that is being conducted by the Geological Survey of Alabama with the sponsorship of the Research Partnership to Secure Energy for America (RPSEA).

The Appalachian thrust belt in Alabama is bounded on the northwest by the gently dipping strata of the Black Warrior Basin and on the southeast by the metamorphic and igneous rocks of the Talladega belt and the Appalachian Piedmont (fig. 2). The thrust belt formed principally during the late Paleozoic Alleghanian orogeny and contains deformed pre-orogenic carbonate rocks of Early Paleozoic age and synorogenic siliciclastic rocks of Late Paleozoic age (e.g., Thomas, 1985; Thomas and Bayona, 2005) (fig. 3). The frontal part of the thrust belt, where shale gas exploration has been concentrated, is dominated by thin-skinned deformation in which Paleozoic strata have been translated cratonward above a basal detachment in Cambrian shale (Rogers, 1950; Thomas, 1985). Thomas (1985) constructed the first comprehensive set of balanced structural cross sections traversing the southern Appalachian thrust belt in Alabama. The increasing availability of seismic data in recent years has added considerably to the understanding of structural style in the southern Appalachians and has resulted in substantial refinement

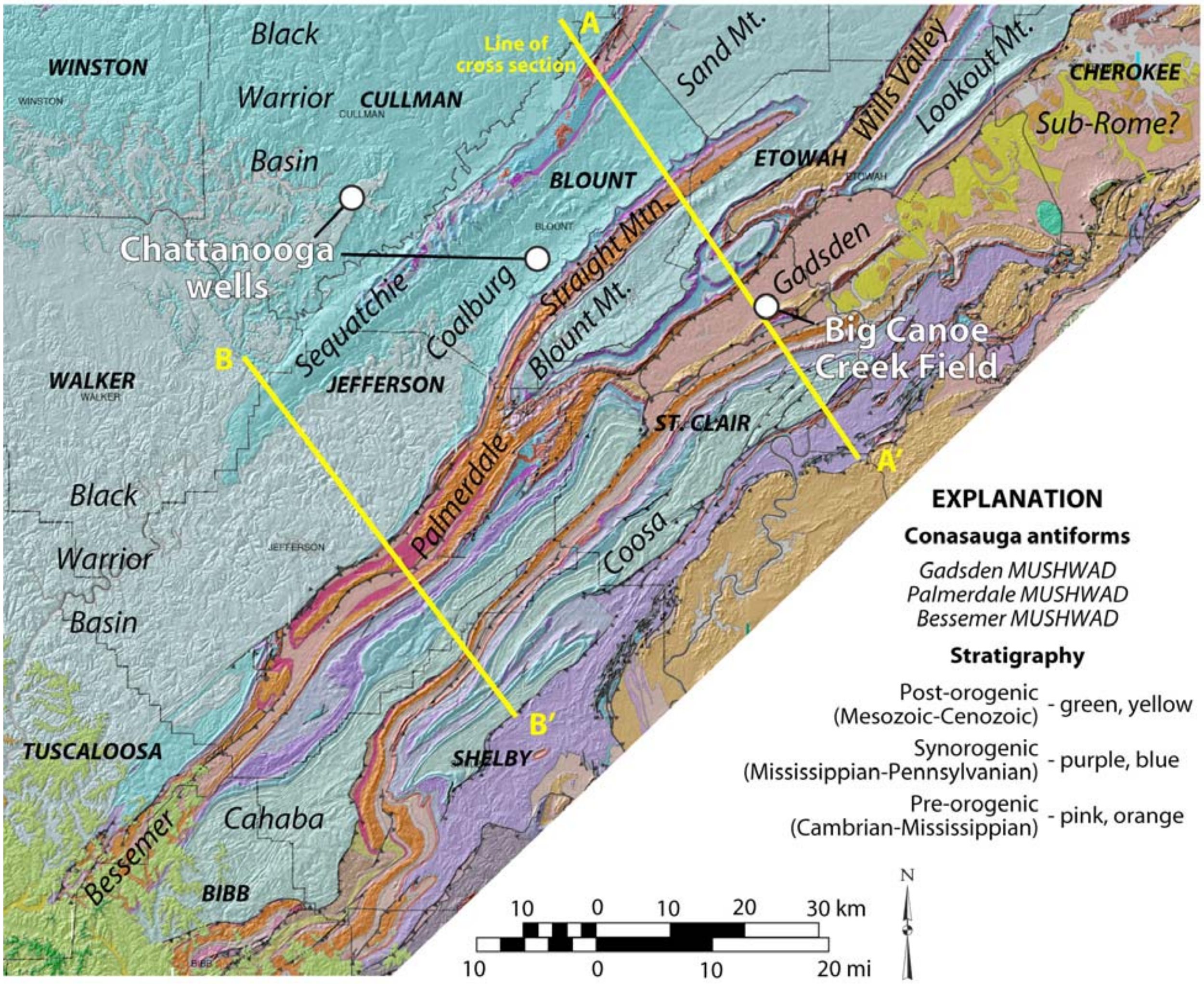

Figure 2.—Geologic map showing major structural features and shale gas development areas in the southern Appalachians of Alabama.

of the regional structural framework (e.g., Thomas, 2001; Maher, 2002; Gates, 2006; Bailey, 2007). This work provides a wealth of information that is useful for characterizing the shale gas potential of thrust belts.

Three distinctive shale plays are active within the southern Appalachian thrust belt of Alabama (Pashin, 2008) (fig. 1). The Cambrian-age Conasauga Formation is geologically the oldest gas shale developed to date and hosts Big Canoe Creek Field, which was the first shale gas field established in Alabama (fig. 2). The Devonian-age Chattanooga Shale is being developed amongst the frontal structures of the thrust belt in northeastern Alabama, and pre-Chattanooga Devonian shale is being explored farther southwest, where the thrust belt is concealed below Mesozoic strata of the Gulf of Mexico coastal plain. Discussion of the shale gas plays begins with an overview of the overall structural style of the southern Appalachian thrust belt and continues with discussion of the Conasauga, Chattanooga, and pre-Chattanooga plays. The paper concludes by synthesizing the results of this analysis into conceptual models that can help guide shale gas development in structurally complex regions.

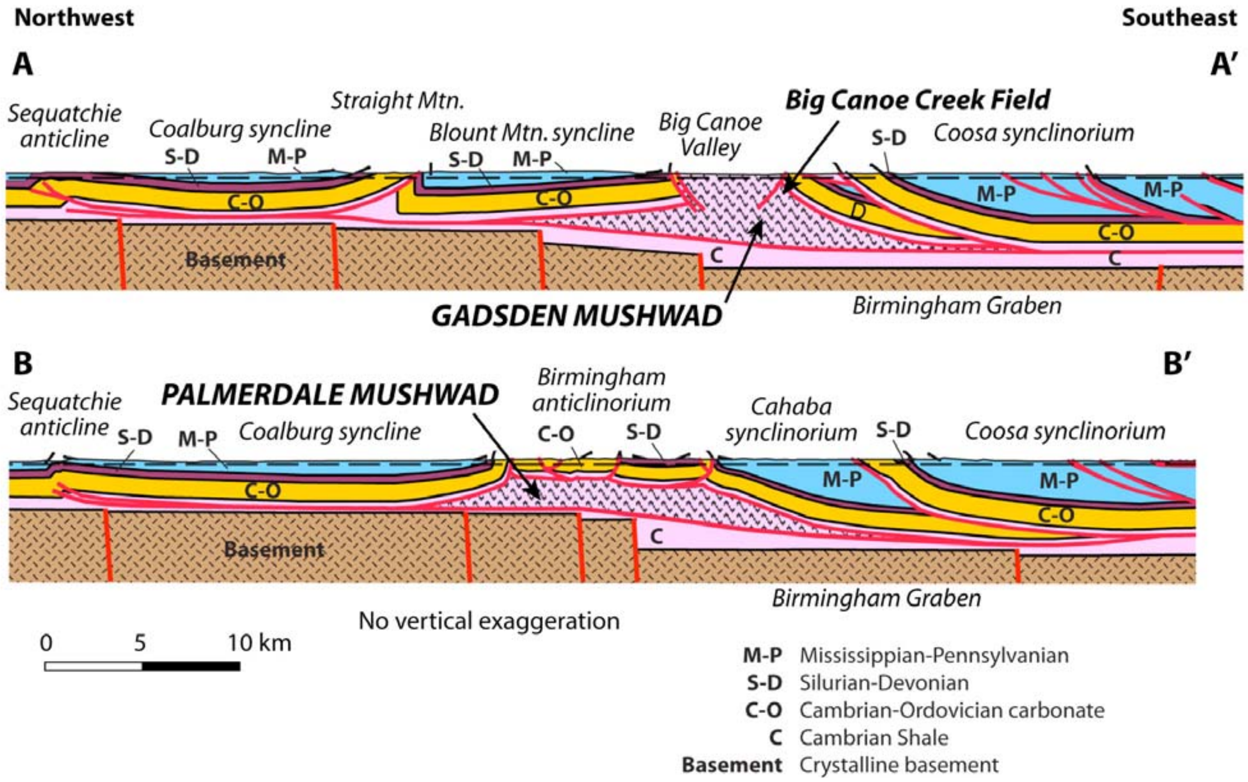

Figure 3.—Structural cross sections showing geometry of the southern Appalachian thrust belt and locations of antiformal shale masses (MUSHWADS) (modified from Thomas and Bayona, 2005). See Figure 2 for location.

STRUCTURAL STYLE

The structural style of the southern Appalachian thrust belt is influenced strongly by the geomechanical properties of the stratigraphic section (Rogers, 1950; Thomas, 1985, 2001). The basal detachment of the thrust belt is developed within a weak Cambrian shale section that overlies crystalline basement (fig. 3). The Cambrian shale hosts a range of structures, ranging from frontal and lateral thrust ramps to giant antiformal stacks of intensely deformed shale that are up to 8,000 feet thick. These antiformal stacks were referred to as MUSHWADs (i.e., Malleable, Unctuous SHale, Weak-layer Accretion in a ductile Duplex) by Thomas (2001) to emphasize the extremely complex deformation within widespread structural duplexes that were preserved below a more gently deformed carbonate roof. Below the shale masses, the basal detachment ramps upward above the edge of the Birmingham graben, which is a Late Precambrian-Early Cambrian rift structure. Structural inversion of the Birmingham graben is thought to have begun during the Taconic orogeny, which may have helped make the shale prone to deformation and overthickening during the Alleghanian orogeny.

Above the Cambrian shale is a stiff carbonate succession of Cambrian-Ordovician age. This carbonate succession is the strongest stratigraphic unit in the thrust belt, and deformation is dominated by frontal and lateral ramps. Silurian through Pennsylvanian strata constitute a large volume of interbedded shale, sandstone, and limestone that is substantially weaker than the Cambrian-Ordovician carbonate. Regardless, frontal ramps commonly rise upward through the complete Cambrian-Pennsylvanian section in the footwalls of the major thrusts (fig. 3). Thus in many areas, the stratigraphic section above the basal detachment was transported cratonward as a single lithotectonic unit. In the hanging walls of the major thrusts, the Cambrian-Ordovician section crops out in a series of ramp anticlines and major fold limbs, whereas the Mississippian-Pennsylvanian section is preserved in broad, flat-bottomed synclines. Locally, however, upper-level thrust flats and secondary detachments are developed at the top of the Cambrian-Ordovician carbonate section and within weak shale units in the Ordovician-Pennsylvanian section (e.g., Thomas, 1985; Pashin and Groshong, 1998; Thomas and Bayona, 2005). Indeed, many second-order folds within the Late Paleozoic section are developed above these secondary detachments in the frontal thrust sheets, and complexly deformed carbonate duplexes are preserved in the interior of the thrust belt adjacent to the metamorphic front.

The shale gas plays of the southern Appalachian thrust belt are in two major structural settings. The Conasauga shale play is restricted to the deformed shale masses constituting the MUSHWADs. The two Devonian shale plays, by contrast, are active in broad synclines and ramp anticlines where the synorogenic Mississippian-Pennsylvanian section is preserved. The gas reservoir in each play has distinctive structural attributes, which are discussed in detail in the following sections.

CONASAUGA SHALE PLAY

Gas was discovered in the Conasauga Formation by Dominion Exploration and Production, Incorporated, in 2005 along the southeastern edge of the outcrop of the Gadsden MUSHWAD (figs. 2, 3). This discovery was based in large part on an early exploratory well drilled by Amoco Production Company in 1984-1985 (J. J. Young 34-2 #1) that had major gas shows in the Conasauga Formation. Production in this area resulted in the establishment of Big Canoe Creek Field, which is the first shale gas field in Alabama (fig. 2). Sixteen wells have been drilled in the field, and 13 of these wells are currently producing.

The productive Conasauga lithology is thinly interbedded shale and micritic limestone that can contain more than 3% total organic carbon. The shale is thinly laminated, whereas the micrite occurs as nodules and thin beds. The Conasauga is of Middle to Upper Cambrian age and has been interpreted as a shoaling-upward succession in which shale grades vertically into inner ramp carbonate facies. The shale is an outer ramp deposit that is thickest in the Birmingham graben (Thomas et al., 2000).

Analysis of cores and outcrops in the Gadsden MUSHWAD indicates that the Conasauga shale facies exhibits many distinctive tectonic structures. Several outcrops reveal large structural panels that strike about N. 55° E. and dip 10° SE, which is consistent with regional dip along the southeastern margin of the Gadsden structure. These panels can be separated by bed-parallel zones of cataclasis that resemble mylonite. Accordingly, the regionally dipping panels are interpreted as fault-bounded blocks, or thrust horses. Elsewhere, the shale can be intensely deformed, and structures include outcrop-scale chaotic folds, isoclinal folds, chevron folds, and faults. One possibility is that these intensely deformed zones help fill space along the margins of the regionally dipping thrust horses.

The Conasauga shale mass contains abundant fractures and calcite veins. These veins range in thickness from a fraction of a millimeter to more than 3 centimeters and have length ranging from a few centimeters to at least 10 meters. Some veins are bed-parallel and planar, whereas others cut across bedding and can be sinuous. Many veins fill wide tension gashes that have an en echelon habit, suggesting mineralization under shear stress. The veins are typically filled with fibrous calcite and contain crack-seal textures that indicate a long and repeated history of opening and cementation. In addition to veins, some shale beds are well jointed. The systematic joints are perpendicular to bedding, strike about N. 45° E, and can be as closely spaced as 1 centimeter.

Although development has been restricted to the Gadsden structure, the Palmerdale and Bessemer MUSHWADs remain undeveloped. The Palmerdale and Bessemer structures are largely concealed below a thin roof of brittle Cambrian-Ordovician carbonate rocks. The Palmerdale structure is in the Birmingham metropolitan area and thus may be difficult to develop, whereas the southwestern part of the Bessemer structure is in rural areas and may therefore be a more attractive exploration target. Other Conasauga shale masses may exist below the Rome thrust sheet in Cherokee and northeastern Etowah Counties, which is developed above a shallow-seated thrust flat (Maher, 2002) and perhaps in adjacent parts of Georgia (Mittenthal and Harry, 2004).

The principal challenges facing development of Conasauga gas resources are drilling and completion. To date, no significant water has been co-produced with gas from Conasauga shale. Wells tend to exhibit exponential decline of gas production, and peak gas rates as high as 318 Mcfd have been reported. Wells are deviated substantially toward the northwest, which reflects the predominant southeastern dip of the thrust horses along the southeast margin of the Gadsden structure. Some fracture zones are highly pressured with gas, which has presented difficulties during development. These pressured gas pockets are interpreted as zones of relict hydrocarbon pressure associated with thermal gas generation. Conasauga wells have been hydraulically fractured using a variety of fluids, and the success of hydrofracturing operations is debatable. The thinly interbedded shale and micrite can be reactive with fluids, thus care must be exercised to avoid formation damage during drilling and completion. In addition, the abundance of open natural fractures in the shale makes hydraulic fracturing difficult because of the potential for leakoff of fracture fluid. Regardless, initial results from several wells have been encouraging, and continued refinement of drilling and completion operations may improve production performance and economics.

CHATTANOOGA SHALE PLAY

Natural gas has been produced from Devonian shale since early last century, but production efforts are just beginning in Alabama. The Chattanooga Shale is a widespread black shale unit that is correlative with shale gas formations in the Ohio Shale of the Appalachian basin, the Antrim Shale of the Michigan basin, and the Woodford Shale of the Arkoma basin. The Chattanooga Shale is widespread in the southern Appalachian thrust belt and the adjacent Black Warrior basin and contains substantial oil shale resources (Rheams and Neathery, 1988). The Chattanooga sits within the thermogenic gas window in much of Alabama (Carroll et al., 1995) and may thus contain significant prospects for natural gas. The Chattanooga disconformably overlies Ordovician through Devonian strata (Kidd, 1975; Thomas, 1988). The Chattanooga is overlain sharply by the Lower Mississippian Maury Shale, which is commonly thinner than 2 feet, and the Maury is in turn overlain by the micritic Fort Payne Chert. The Chattanooga Shale in Alabama was apparently deposited in dysoxic to anoxic subtidal environments in a cratonic extension of the Acadian foreland basin (e.g., Ettensohn, 1985).

Geomet, Incorporated, has been developing Chattanooga prospects in two areas along the frontal structures of the Appalachian thrust belt in Cullman and Blount Counties (fig. 2). In each area the shale is about 40 feet thick and is at depths between 1,600 and 2,100 feet (Rheams and Neathery ,1988; Pashin, 2008). Each area of development is structurally distinctive. The northwestern area in Cullman County is at the fold hinge defining the boundary between the distal forelimb of the Sequatchie anticline and the Black Warrior basin. The southeastern area, by contrast, is in the hinge between the flat-bottomed Coalburg syncline and the dipping backlimb of the Straight Mountain structure, which is a large ramp anticline associated with a major backthrust (fig. 3).

The salient type of structure in the southern Appalachian thrust belt is a ramp anticline with a steep or vertical forelimb and a gently dipping backlimb (figs. 4, 5). Fold and thrust geometry are intimately related, and recent structural interpretations indicate that significant variations of geometry that may affect reservoir performance occur within and among the major Appalachian structures (e.g., Maher, 2002; Groshong, 2006; Gates, 2006). Thrust faults in the southern Appalachians have been interpreted to include listric thrust faults and ramp-flat structures. The Sequatchie and Wills Valley anticlines, for example, have been interpreted to be at least partly developed above listric thrust faults (Maher, 2002; Groshong, 2005, 2006).

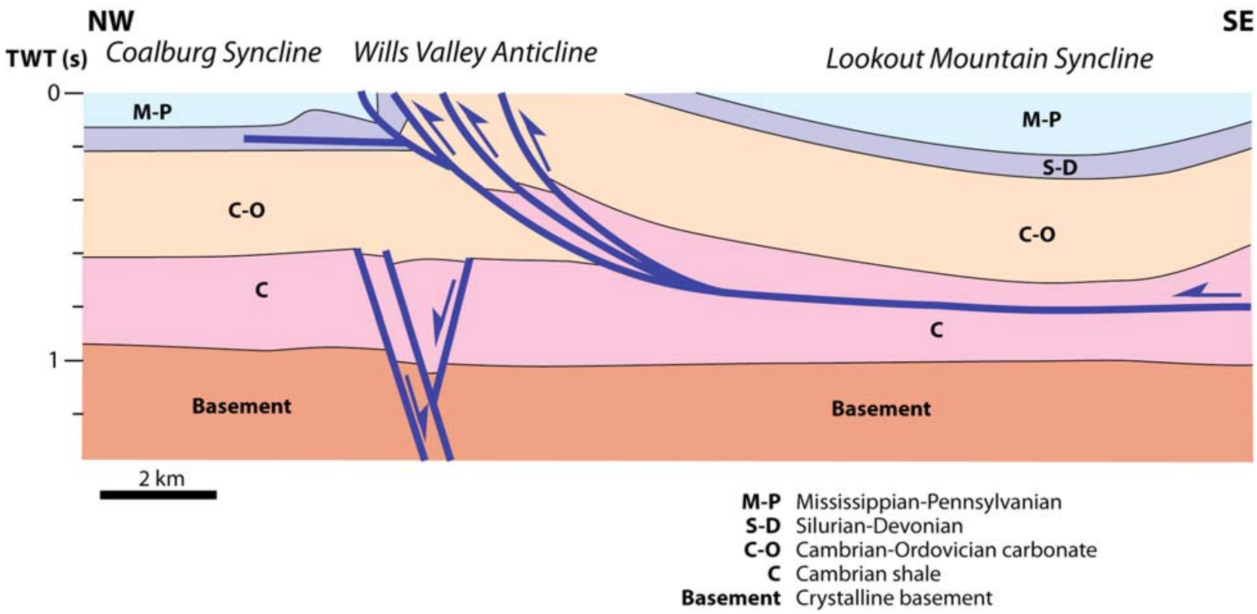

Figure 4.—Structural interpretation based on seismic profile of the Wills Valley anticline and associated structures above a listric thrust fault (modified from Maher, 2002).

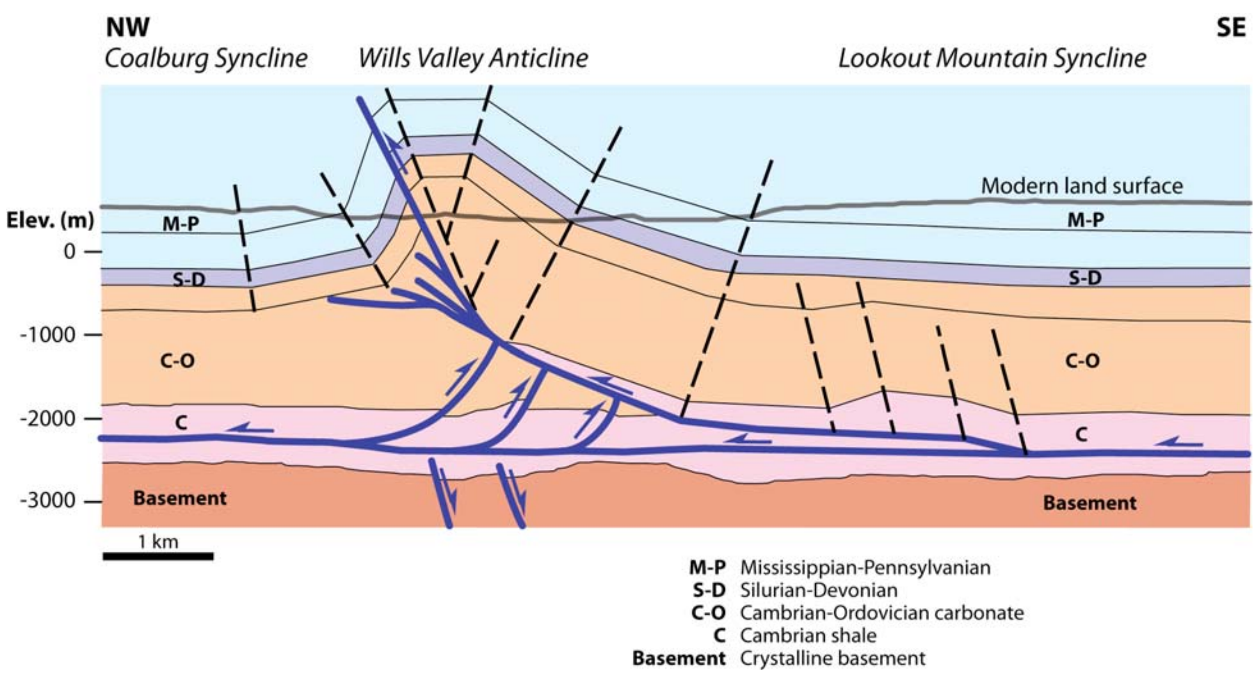

Figure 5.—Structural interpretation based on seismic profile of the Wills Valley anticline and associated structures above a thrust fault with multiple dip bends (modified from Gates, 2006).

Seismic data have been used to constrain along-strike variation in the Wills Valley anticline, and balanced cross sections document the consequences of changing fault geometry on fold geometry. Deformation above a listric thrust near the southwest terminus of the Wills Valley anticline is associated with a broadly folded backlimb structure lacking distinct fold hinges in the Lookout Mountain syncline (Maher, 2002) (fig. 4). Farther northeast, this same thrust fault, while maintaining an overall listric geometry, is interpreted to contain multiple dip bends that localize distinct fold hinges in the backlimb of the anticline. Importantly, southern Appalachian fold hinges are zones of enhanced natural fracturing associated with sweet spots for gas and water production in coalbed methane reservoirs (Pashin and Groshong, 1998; Pashin, 2005), and similar hinge effects may influence the performance of shale reservoirs.

The Chattanooga Shale is part of a weak lithotectonic unit that is bounded above and below by stiff carbonate units. In places, the shale can be well jointed (fig. 6). Systematic joints tend to be perpendicular to bedding and strike about N. 60°E. Accordingly, these joints are interpreted to be pre-kinematic structures that formed and were then rotated with the fold limb. Pre-kinematic joints with similar orientation have been identified the length of the southern and central Appalachians and have been interpreted as the product of a continent-wide stress field associated with the early assembly of the Pangaean supercontinent (Engelder and Whittaker, 2006). In many fold limbs, however, the shale can contain a multitude of shear zones characterized by faulting and small-scale folding. These shear zones apparently reflect flexural slip of incompetent shale between competent carbonate units within large-scale folds limbs.

Production data are just beginning to be reported, and initial production rates from vertical wells are as high as 160 Mcfd, which indicates significant economic potential. A key difference between Chattanooga and Conasauga production is that a significant amount of water is co-produced with the gas from the Chattanooga Shale. In most wells, slightly more than 1 bbl of water per Mcf of gas is being produced, which is comparable to many coalbed methane wells in Alabama. Joints and shear structures appear to give the Chattanooga significant hydraulic conductivity, and the shale crops out near the crests of the major Appalachian folds, which constitute major zones of fresh-water recharge. Fresh-water recharge has resulted in significant late-stage biogenic gas accumulations in the Antrim Shale of the Michigan basin (Martini et al., 1998), and late-stage biogenic gas has been identified in coal along the Appalachian frontal structures in Alabama (Pashin, 2007). However, isotopic data from the produced gases are required to verify the occurrence of late-stage biogenic gas. Regardless, early production results indicate that managing co-produced water is a significant aspect of shale gas production amidst the Appalachian structures in Cullman and Blount Counties.

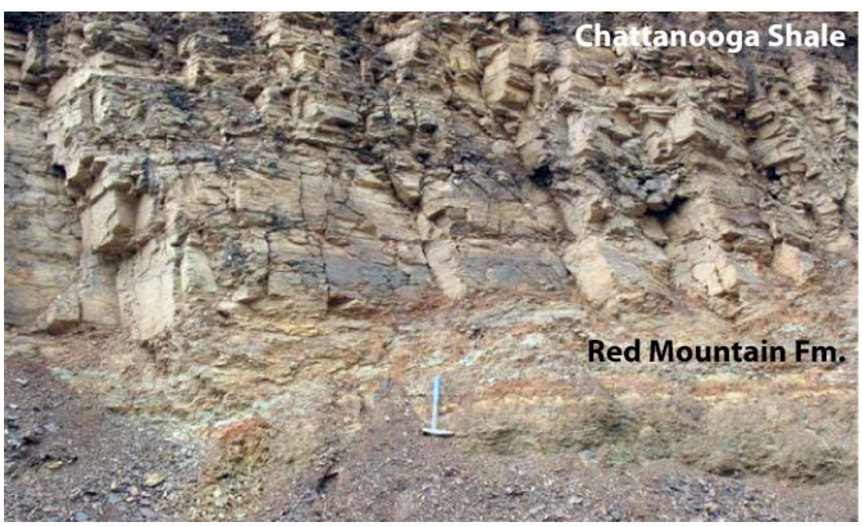

Figure 6.—Outcrop in the backlimb of the Sequatchie anticline showing jointed Chattanooga Shale disconformably overlying the Silurian-age Red Mountain Formation (photograph courtesy of Dan Irvin).

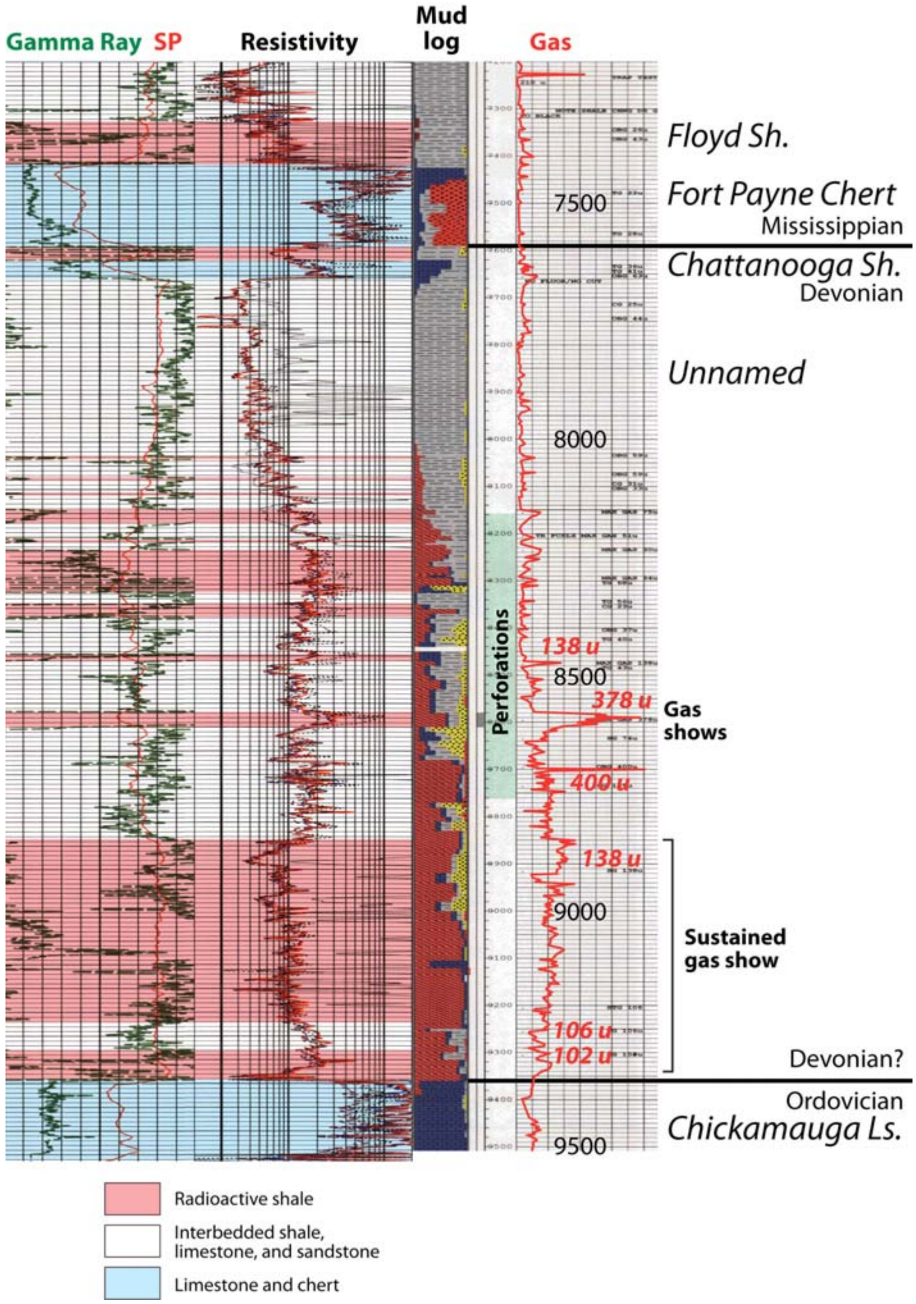

Figure 7.—Geophysical well log and mud log showing relationship of gas shows to the Ordovician-Mississippian section in the Bayne-Etheridge 36-9 #1well.

PRE-CHATTANOOGA DEVONIAN SHALE PLAY

Where the Appalachian thrust belt underlies the Gulf of Mexico coastal plain, EOG Resources, Incorporated, drilled an exploratory well (Bayne-Etheridge 36-9 #1) that reached a total depth of 9,514 feet. The well encountered major gas shows from depths of 8,470 to 9,460 feet in a thick, unnamed succession of interbedded shale and limestone (fig. 7). This interval is presumably of Devonian age and is significantly older than the Chattanooga Shale. This section was intersected in the backlimb of a large ramp anticline that had been explored previously by Arco and Amoco in the 1980s (fig. 8).

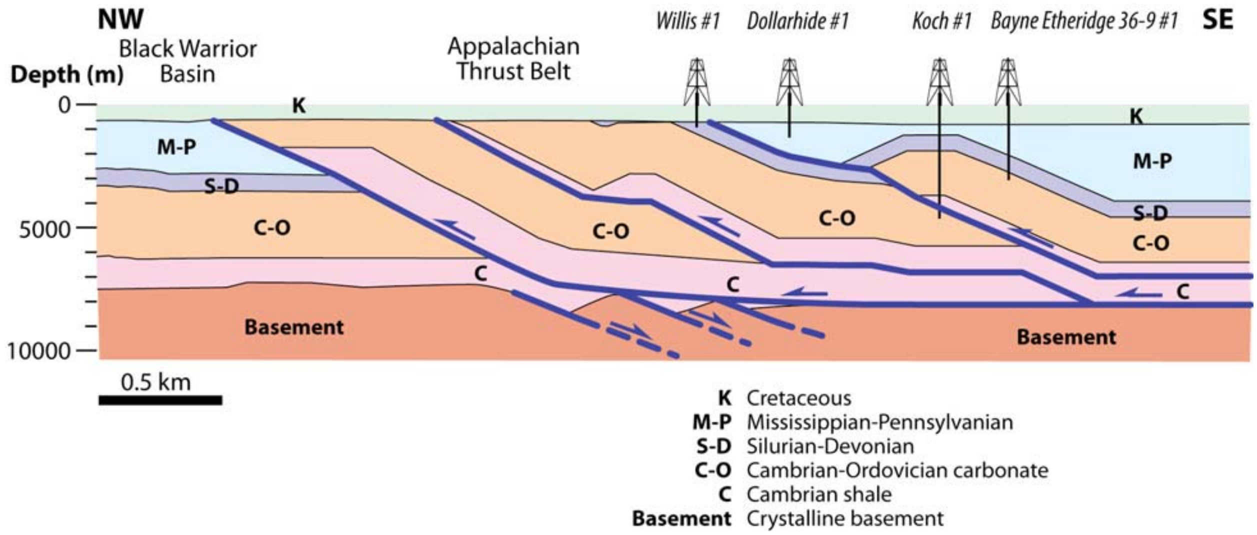

Figure 8.—Structural interpretation based on seismic profile of ramp-flat thrust belt structure below the Gulf of Mexico coastal plain (modified from Bailey, 2007).

A seismic profile interpreted by Bailey (2007) indicates that thrust belt structure below the Gulf of Mexico coastal plain is dominated by ramp-flat structure that differs significantly from the exposed thrust belt farther northeast (fig. 8). A large frontal ramp defines the boundary between the Appalachian thrust belt and the Black Warrior basin, and repetition of the Cambrian-Ordovician carbonate section in the hanging wall defines an imbricate pair of thrust panels with large displacement. A large ramp anticline is developed in a third structural panel in which the Silurian-Devonian section has been transported just beyond the edge of the upper flat. The Koch well was drilled by Arco and Amoco in the 1980s and penetrated the crest of the anticline as well as a thrust fault that places upper Conasauga limestone on the Cambrian-Ordovician Knox Group. The Bayne-Etheridge well was drilled in the backlimb of the anticline, and the dipmeter log indicates that dip is about 20° SE.

The well was perforated and cored at various intervals between 8,160 and 8,760 feet. The well was hydrofractured with CO_2 foam, tested with a production rate of 120 Mcfd, and is currently shut in. The core contains radioactive black shale with gray shale, argillaceous limestone, and crinoidal packstone-wackestone (fig. 7). Dipmeter and formation micro-imager logs indicate that, although regional dip is about 20°, the shale interval is complexly deformed (fig. 9). Analysis of these logs indicates that dip varies between 10 and 40°, and some significant dip discordances correspond with zones of deformation that are interpreted as shear zones. Hence, the pre-Chattanooga Devonian section constitutes a weak lithotectonic unit in which parasitic folds and faults are superimposed on a regionally dipping structural panel. Importantly, two of the most prominent gas shows correspond with shear zones.

Another zone of interest is a thick, radioactive shale zone between 8,840 and 9,360 that overlies the Ordovician-age Chickamauga Limestone (fig. 7). The dipmeter log indicates that deformation within this zone resembles that in the shale higher in section. Regardless, this deeper interval corresponds with a sustained, low-level gas show on the order of 102 to 138 units, which suggests that the shale is saturated with gas. The consistency of this show, moreover, indicates that the gas pressure in the shale exceeded the pressure of the drilling fluid. Therefore, the thickness of the shale coupled with the consistency of the gas show suggests that it may provide a significant opportunity for completion.

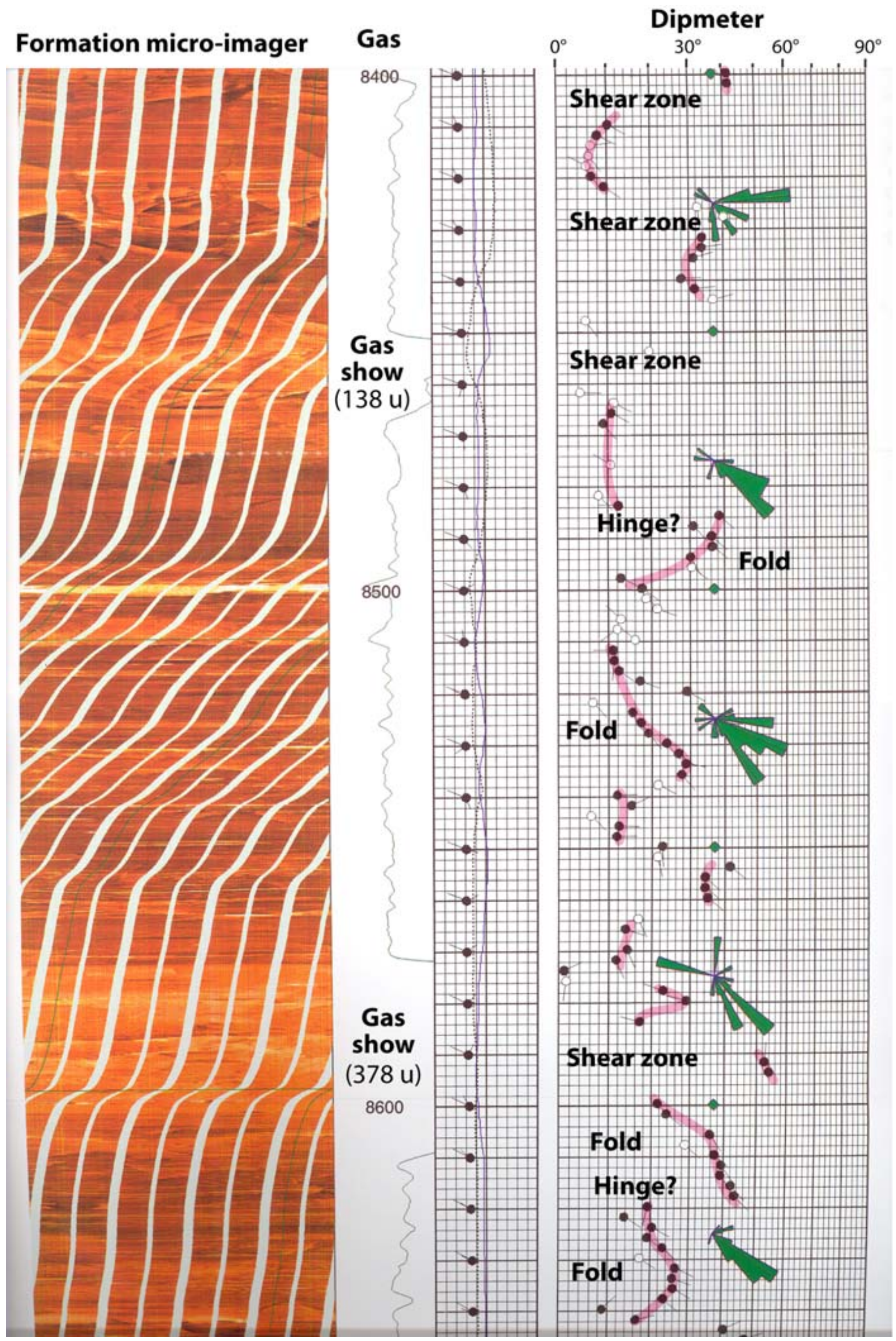

Figure 9.—Formation micro-imager and dipmeter logs showing complex deformation associated with gas shows in the Bayne-Etheridge 36-9 #1well.

DISCUSSION AND CONCLUSIONS

Multiple shale gas plays are emerging in Cambrian through Devonian strata of the southern Appalachian thrust belt, and geologic structure controls the distribution of proven and prospective reservoirs (figs. 10, 11). These reservoirs are in mechanically weak lithotectonic units, and reservoir development is influenced by basement structure and thrust kinematics.

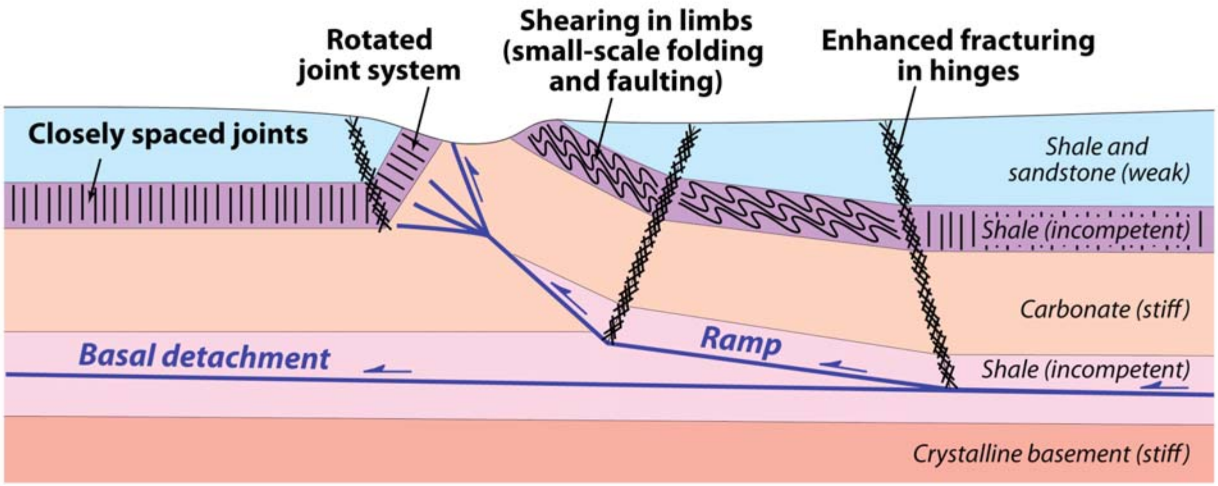

Figure 10.—Conceptual model showing relationship of reservoir-scale deformation in shale to thrust belt structure.

The Conasauga Formation (Cambrian) contains the world's oldest shale gas reservoirs in an outer ramp facies consisting of thinly interbedded shale and micrite. The productive facies was deposited in an Early Cambrian basement graben that was partially inverted during the Taconic orogeny. During Alleghanian thrusting, the shale was deformed into giant antiformal stacks that rest on the basal detachment of the thrust belt (fig. 11). These antiformal stacks approach a thickness of 8,000 feet. Internally the stacks contain structural panels that maintain regional dip. These panels are separated by intensely deformed regions that include trains of folds and zones of intense cataclasis. The reservoirs have characteristics of both fractured and microporous gas reservoirs and are notable for intense gas pressure in some fracture networks. Thermogenic charge from deep within the shale bodies appears to be the source of high gas pressure.

Devonian black shale is being developed at multiple locations within the southern Appalachians in Alabama, and production has been established in the Chattanooga Shale in the frontal part of the thrust belt. The Devonian shale section forms a mechanically weak unit that was carried above a stiff Cambrian-Ordovician carbonate section. Thrust faults have a ramp-flat to listric geometry that determines the location and geometry of fold limbs and hinges (figs. 10, 11). Shale in fold limbs can contain transported orthogonal joint networks and can contain folds and faults formed by layer-parallel shear (fig. 10). Fracturing in fold hinges and shear zones in fold limbs may increase permeability and may correspond with productivity sweet spots (fig. 11). However, zones with high natural permeability should be approached with caution because of potential thieving of hydraulic fracturing fluid. Breached anticlines are major zones of fresh-water recharge, which can facilitate mixing of thermogenic and late-stage biogenic gases in unconventional reservoirs. Regardless of the origin of the gas, a significant quantity of water is co-produced with gas from the Chattanooga Shale.

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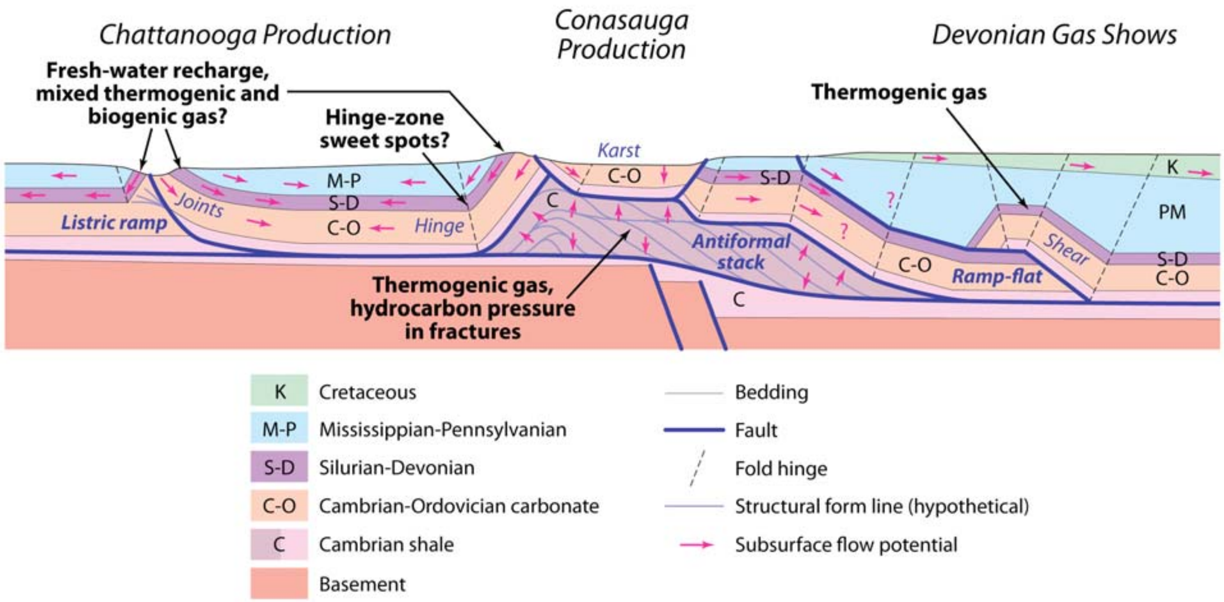

Figure 11.—Conceptual model of the geology of shale gas reservoirs in the southern Appalachian thrust belt of Alabama.

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